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Hybrid orthosis system with a variable hip coupling mechanism

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Abstract—**Existing reciprocating gait orthoses, to help restore gait to individuals with paraplegia, have a fixed 1:1 hip flexion/extension coupling ratios (FECR), limiting stride length and gait speed. The purpose of this study was to develop a hip reciprocating mechanism for the hybrid orthosis system that is capable of variable hip FECR. The design of the new variable hip reciprocating mechanism incorporates a hydraulic system which utilizes solenoid valves to control coupling between cylinders linked to each hip joint of the orthosis. A specific set of valves are pulsed to achieve continual variable hip coupling. It was shown that piston velocity was inversely proportional to pulse width and also dependent on pulsing frequency. Internal losses in the hydraulic hip reciprocating mechanism occur primarily in the cylinders. Feedback control will be achieved with a dual layer gait event detector consisting of a fuzzy inference system and a set of supervisory rules.**

Keywords—**Hybrid orthosis system, reciprocating gait orthosis, hip reciprocating mechanism**

I. Introduction

The reciprocating gait orthosis (RGO) utilizes a mechanism that reciprocally couples hip extension with contralateral hip flexion. In other words, the torque used to extend the stance hip is transferred to the contralateral swing hip to assist in hip flexion. This hip reciprocating mechanism has been shown to reduce sagittal trunk tilt during gait in individuals with paraplegia [1]. An assistive gait technology for individuals with spinal cord injury known as the hybrid orthosis system (HOS) combines the RGO with functional neuromuscular stimulation (FNS) control of the lower extremity muscles. The RGO locks the lower extremity joints during stance while FNS controls the lower extremity joints during swing. However, the current hip reciprocating mechanism used by the RGO allows only a fixed 1:1 hip flexion/extension coupling ratio (FECR), limiting hip flexion to the extent of contralateral hip extension. Thus, stride length and gait speed are limited. A hydraulic approach has been proposed in developing a hip reciprocating mechanism capable of variable hip FECRs.

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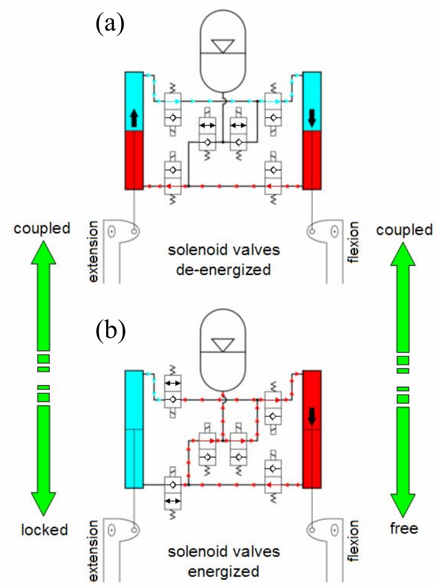

Fig. 1. Hydraulic Hip Reciprocating Mechanism. Continuous variable hip coupling is achieved by pulsing the solenoid valves.

II. Methodology

1) *Hydraulic Hip Reciprocating Mechanism*: The design of the hydraulic hip reciprocating mechanism (HHRM), shown in Fig. 1a, consists of a double acting hydraulic cylinder linked via a separate mechanical transmission to each hip joint of the orthosis. The corresponding ports of the opposing cylinders are connected by tubing and fittings to produce a closed hydraulic circuit. Hip extension forces the ipsilateral piston to extend, which further pressurizes the contralateral piston to retract, resulting in contralateral hip flexion. The hip joints can be locked, freed to move, or coupled by energizing specific 2-way, 2-position solenoid valves that are positioned between the cylinders. An accumulator provides pressure relief during the actuation of a cylinder by the freed ipsilateral hip.

The combination of closing and/or opening of certain solenoid valves can result in either fixing hip reciprocation to a 1:1 FECR (Fig. 1a) or locking one hip in a desired orientation and disengaging the contralateral hip from reciprocation (Fig. 1b). If the stance hip was locked in extension and the swing hip freed to flex the orthosis would no longer be restricted to a 1:1 FECR and variable coupling ratios could be achieved. This approach to facilitate variable FECRs, however, leaves the flexing swing hip to be controlled only by FNS, resulting in unpredictable stride lengths. In order to achieve variable hip FECRs while maintaining continual hip coupling from the HHRM, the solenoid valves are synchronously pulsed between states (a) and (b) in Fig 1. During valve pulsing, the extending stance

TABLE I
HYDRAULIC HIP RECIPROCATING MECHANISM
COMPONENT SPECIFICATIONS

Component	Solenoid Valve	Cylinder	Accumulator
Manufacturer	Allenair	Clippard	Hydac
Line	General Purpose	Minimatic	Welded
Type	2-way, 2-position	Double Acting	Diaphragm
Orifice	2.38 mm	-	-
Port	1/8" NPT	1/8" NPT	3/8" NPT
C_V	0.195	-	-
Stroke	-	76.20 mm	-
Bore	-	22.23 mm	-
Rod Diameter	-	6.35 mm	-
Size	-	-	0.075 L
Gas Precharge	-	-	4 bar
Max Pressure	NO: 8.62 bar NC: 10.34 bar	68.95 bar	248.21 bar

hip is transitioning between a locked and coupled state, while the flexing swing hip is transitioning between a coupled and freed state. Thus, valve pulsing serves both to slow down the extending hip relative to the flexing hip and maintain hip coupling. Accordingly, the FECR can be modulated by varying the pulse width of the valves.

2) *Hydraulic Component Selection*: Preliminary hydraulic component selection was done utilizing the net applied hip moments and hip angular velocities from an existing 3-D computer model of gait with a HOS [2]. Using an array of cylinder sizes, the maximum flow rates and pressures within the system were calculated under the dynamics of HOS gait. We are currently aiming toward using off the shelf components. The goal is to select a cylinder bore size that minimizes system peak pressures and flow rates and select solenoid valves that allow for as large a flow rate as possible with minimal pressure losses and sustain a sufficiently large pressure differential. Size, weight, and power consumption of these components were also considered. Table I shows the components most appropriate for the HHRM. A rack-and-pinion gear mechanism was designed as the hip-to-cylinder transmission. The cylinder piston displacement per degree hip rotation is 0.55 mm/deg. The maximum estimated piston velocity during gait with the rack-and-pinion transmission is approximately 40 mm/s. The theoretical torque per unit pressure and displacement volume per degree hip rotation of the selected cylinder and hip-to-cylinder transmission is 1.23 Nm/bar and 0.215 cm^3/deg respectively.

3) *Valve Pulsing*: Experiments were conducted to access how varying the pulse width of a solenoid valve (Allenair Corp., Mineola, NY) would affect the output piston velocity. The influence of pulsing frequency on external vibration of the hydraulic system was also examined. A normally open solenoid valve (Table I) was connected between the ports of a double-acting, 27 mm bore, cylinder. Pressure sensors (Gems Sensors Inc., 1200 Series, Plainville, CT) were positioned at both ports of the cylinder. Reflective markers were placed on the cylinder to measure the displacement of the piston using the VICON Motion Analysis System. A mass of 16 kg was connected in series with a load cell (Lebow Products Inc., Model 3167, Columbus, OH) at the end of the piston rod. The piston was fully retracted at the onset of each trial. Valve pulsing started after the mass was released and allowed to fall. This was repeated with different pulse widths and pulsing frequencies.

4) *Bench Testing of the HHRM*: The initial HHRM prototype was stiff and difficult to actuate manually. Bench testing experiments of the prototype was setup to evaluate: (1) the reciprocal coupling between cylinders, (2) pressure losses through the valves, fittings and tubing, (3) the effect of valve orifice size on the system stiffness, and (4) the mechanical efficiency of the hydraulic system. Three cylinders of different construction (bore size versus rod diameter, head inner diameter, and port size) and valve combinations (solenoid and manual shutoff ball valves) were used in the HHRM. ISO VG 46 hydraulic oil was used as the medium. A load cell and handle were attached in series to the rod clevis of the right (actuator) cylinder. A mass was attached to the rod clevis of the left (follower) cylinder. Digital pressure sensors were placed at each cylinder port to measure internal static pressure. Reflective markers were placed on the cylinders to monitor piston position using the VICON Motion Analysis System. At the start of each trial, the actuator cylinder was fully retracted and the follower cylinder was fully extended. A trial of the experiment consisted of fully extending the actuator cylinder by pulling down on the handle and then returning the cylinder to its fully retracted position. This was repeated for several cycles during each trial. In the case of the manual shutoff ball valves, the valves were opened at several intermediate valve open states (VOS): fully open, ¾ open, ½ open, and ¼ open. Also, the cylinder was cycled at roughly 3 different speeds (slow, medium, and fast) defined by the operator.

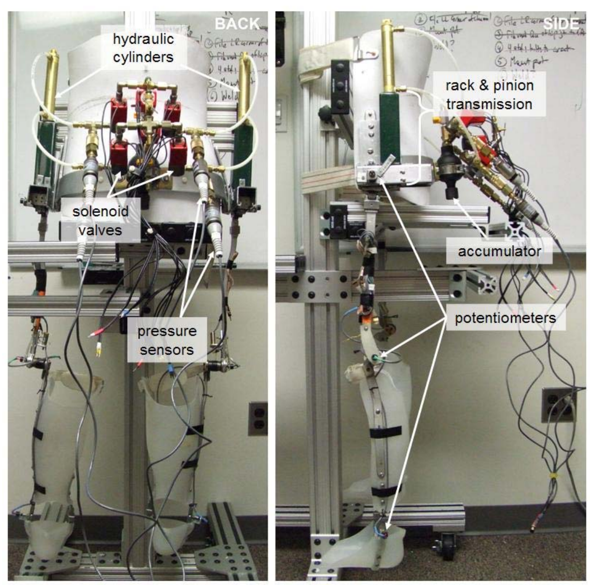

Fig. 2. Instrumented Hydraulic Reciprocating Gait Orthosis.

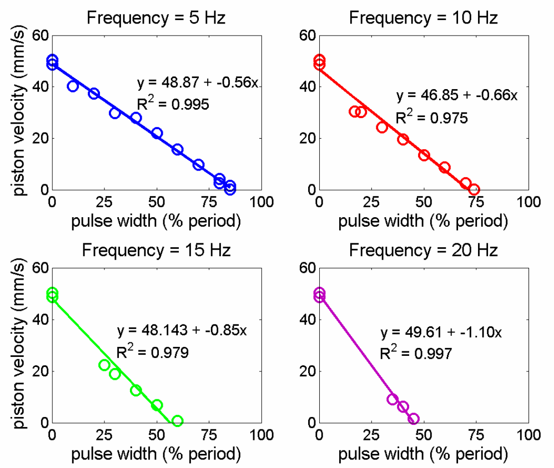

Fig. 3. Piston velocity (mm/s) vs. pulse width (% period) for multiple frequencies during pulsing of the Allenair valve.

5) *Feedback Control*: The orthosis provides a structure to mount sensors for feedback control during gait. The instrumented gait orthosis (Fig. 2) has potentiometers (Vishay Spectrol, Malvern, PA) mounted to the hip, knee, and ankle joints to measure the sagittal joint rotation angles. Force sensing resistors (B & L Engineering, Tustin, CA) will be placed at the soles of the feet to capture foot-ground contact information.

The controller currently runs on xPC Target/Simulink (MathWorks, Inc., Natick, MA). The core of the controller utilizes a gait event detector which incorporates a dual layer control algorithm: (1) fuzzy inference system (FIS) and (2) supervisory rules [3]. The gait cycle was divided into six gait events with respect to the right limb.

The first control layer is a Takagi-Sugeno-Kang FIS that serves to estimate the gait event. There are ten inputs into the FIS (six joint angles and four foot pressure sensors). Six membership functions, one for each fuzzy set (gait event), occupies the domain of each input. The shape of each membership function is the Gaussian probability density function of the input during a particular gait event. The FIS incorporates six IF-THEN rules. The FIS uses six singleton

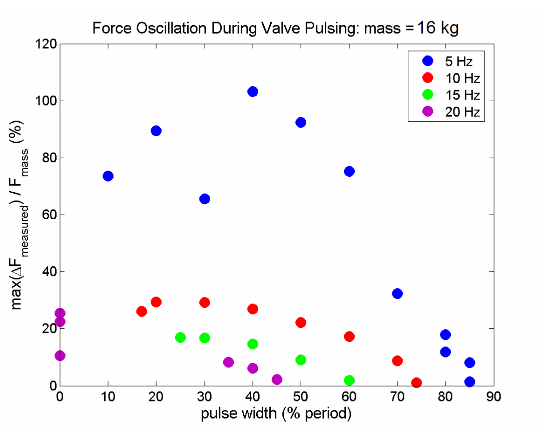

Fig. 4. Normalized maximum change in force (% force applied by mass) vs. pulse width (% period).

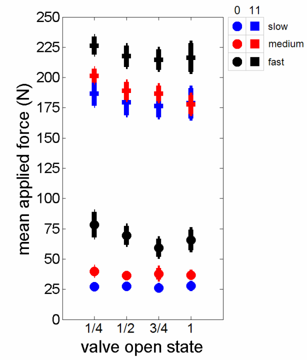

Fig. 5. The influence of orifice size on applied force on the actuator cylinder. For no load and 11 kg applied to the follower cylinder.

output membership functions.

The second control layer is a set of supervisory rules which serve to refine the gait event estimates output from the FIS [3]. There are two basic supervisory rules. The first rule limits the minimum duration of a gait event. The duration of each gait event must be at least 70% of the running average duration of all gait events. The second rule guarantees that the gait events are predicted in a sequential order. If the FIS estimates a gait event that has already occurred in the gait cycle, the supervisory control layer disregards the estimate and maintains the current gait event. However, if the FIS prematurely skips a gait event, the supervisory layer will only advance one gait event from the previous gait event before the change. The output gait event is then sent to the muscle stimulator and the solenoid valve control circuitry.

A running mean and standard deviation of the range of each sensor input during each gait event will be continuously occurring during gait. These parameters will be used to constantly update the input membership functions of the FIS. The shapes of the membership functions will be initialized by gait data of able-body individuals walking with the orthosis at multiple stride lengths. This type of closed-loop architecture in the gait event detector will allow the flexibility of accommodating for variable stride lengths.

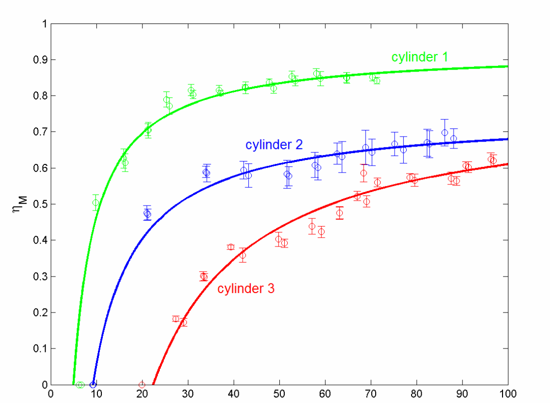

Fig. 6. Mechanical efficiency versus mean applied force on the actuator cylinder when the HHRM was configured with cylinder types of differing construction.

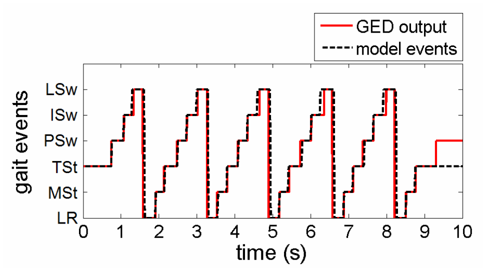

Fig. 7. Preliminary data from gait event detector. LR = loading response, MSt = midstance, TSt = terminal stance, PSw = pre-swing, ISw = initial swing, LSw = later swing.

III. Results

1) Valve Pulsing: The valve pulsing experiments show that piston velocity is inversely proportional to pulse width (Fig. 3). In addition, the piston velocity is dependent on the pulsing frequency. Fig. 4 shows that the force oscillation amplitude, normalized by the applied force due to the falling mass, decreases with increasing pulsing frequency.

2) Bench Testing: During actuator cylinder extension at an average rate of approximately 20 mm/s, the median pressure loss between cylinder ports (through two solenoid valves) was approximately 0.9 bar with an interquartile range of 0.3 bar when no load was applied to the follower cylinder. At a same flow rate, when a 11 kg mass was applied to the follower cylinder, the median pressure drop between cylinder ports was approximately 1.1 bar with an interquartile range of 0.8 bar.

When the ball valves are fully open we can consider that the port-to-port connections between the cylinders are composed of only tubing and fittings. At a mean actuator cylinder extension rate of 200 mm/s the mean pressure drop on the rod side of the system for both no load and 11 kg cases applied to the follower cylinder were less than 0.1 bar.

Fig. 5 shows the mean applied force (N) as a function of both VOS and three actuator cylinder pulling speeds. Notice that the applied force does not change significantly at the different valve open states.

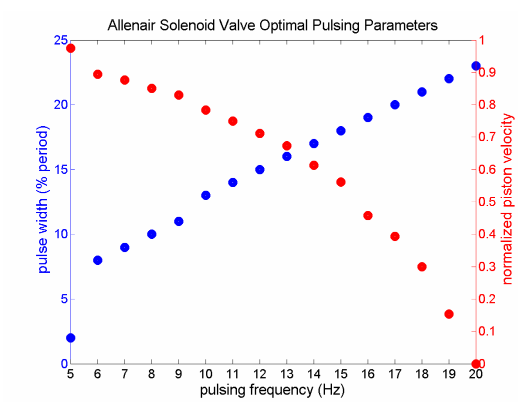

Fig. 8. Allenair Solenoid Valve Optimal Pulsing Parameters.

Fig. 6 shows that the HHRM mechanical efficiency (η_M) varies significantly depending on the geometry of the cylinder components.

3) Feedback Control: Fig. 7 shows the accuracy of the gait event detector using inputs from a 3-D computer model of gait with the HOS [2]. The joint angle inputs were corrupted with a ±3 deg noise signal and the foot-ground contact force inputs were corrupted with a ±10% body weight noise signal.

IV. Discussion

The dependency of the piston velocity on the pulsing frequency can be attributed to the long response time of the solenoid valves (≈ 12 ms pulse on and 40 ms pulse off). System vibration can be minimized by selecting the maximal achievable frequency and minimal achievable pulse width for a chosen FECR. Fig. 8 plots the minimum achievable pulse width of the Allenair solenoid valve and normalized piston velocity with respect to the maximum achievable pulse frequency of the valve. If the objective was to slow the extending hip to half the rotational speed of the flexing hip (= 2:1 FECR), the optimal pulsing frequency and pulse width would be approximately 15.5 Hz and 19% period respectively.

The bench testing results indicate that the pressure losses through the solenoid valves and the fittings and tubing used in the HHRM are not significant. Also, valve orifice size does not seem to have a significant effect on the stiffness of the HHRM. However, the low mechanical efficiency of cylinders 2 and 3, show that much of the pressure loss in the system can occur internally within the cylinder.

Future work will include experimenting with able-bodied individuals walking with the HHRM and the subsequent evaluation of the gait event detector with this able-body data.

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